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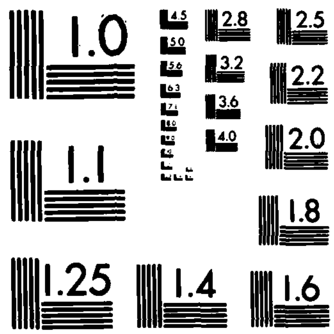

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The Response of an Albedo Neutron Dosimeter to Moderated AmBe and ^{252}Cf Neutron Sources

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The response per Rem of an albedo neutron dosimeter has been determined for 56 neutron spectra which were generated by moderating AmBe and ^{252}Cf neutron sources with various combinations of Lucite, polyethylene, and steel. The spectra were determined by using Bonner spheres and were further characterized by using commercially available 9-in., 3-in., and bare BF_3 tube detectors and an Anderson-Braun-type Rem-meter. The average energy of the spectra ranged from approximately 0.4 to 4.5 MeV. The ratio of the 3-in. detector response to the 9-in. detector response varied from about 0.3 to 3, and the ratio of the bare detector response varied from 0.04 to 3. The response per Rem of the albedo dosimeter, a ^{6}LiF-^{7}LiF detector pair behind a cadmium shield encased in a plastic badge, varied by more than a factor of seven. Our experiments showed that for this type albedo dosimeter, the bare to 9-in. detector ratio is more appropriate for reducing

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19. ABSTRACT (Continued)

energy dependence than the 3-in. to 9-in. ratio, which is recommended for completely cadmium-encased albedo dosimeters, and is often used for other types of albedo dosimeters. Using both ratios gives optimum results; the average error due to energy dependence was reduced to about ±10%. Using the response ratio of a detector in front of the cadmium shield to the one behind the shield to correct for energy dependence was also effective for these spectra; the average error was approximately ±20%. Keywords:

CONTENTS

THE RESPONSE OF AN ALBEDO NEUTRON DOSIMETER TO MODERATED AmBe AND ^{252}Cf NEUTRON SOURCES

INTRODUCTION

The U.S. Navy uses an albedo neutron dosimeter badge for the determination of neutron personnel exposures in various shore and Fleet environments. It is well known that this type of neutron dosimeter is highly energy dependent, giving a large overresponse to lower energy neutron spectra when calibrated by using unmoderated AmBe or ^{252}CF neutron sources [1]. For some types of albedo personnel dosimeters it has been shown that appropriate corrections for the overresponse can be derived from measurements of the neutron spectrum made with survey instrumentation, e.g., a 9-in. polyethylene spherical Remmeter, and a 3-in. cadmium-covered polyethylene sphere surrounding a BF_3 tube detector [2].

The purpose of this study was to determine the response of the Navy albedo dosimeter badge to various neutron spectra, and to determine appropriate methods of eliminating or reducing the energy dependence of the dosimeter by using either survey instrumentation data, or the response of a second detector in the badge.

THE DOSIMETER BADGE

The albedo neutron dosimeter badge used in this study is of the type devised by Falk [3] in which two pairs of ^{6}LiF and ^{7}LiF thermoluminescence detectors (TLD) are situated on each side of a cadmium disc as illustrated in Fig. 1(a). Since the Navy uses detectors held in dental-film-size cards, it was necessary to use two cadmium filters as shown in Fig. 1(b). The detector cards and filters are held in a plastic TLD (or film) badge. The badge, shown in Fig. 2, is 4.5 × 5.8 × 0.9-cm thick and has a wall thickness of 0.25 cm. The cadmium filters are each 44 × 15 × 0.38-mm thick. To assure good coupling to the wearer, the badge is equipped with a belt loop. The albedo neutron dosimeter badge routinely used in most Navy environments, the DT-583, is identical to this badge except that only one cadmium shield and one pair of TLDs are used. The detectors are located between the body and the cadmium shield. A variation of this design is also used at the Naval Research Laboratory (NRL). The NRL design uses two cadmium shields 20 × 20 × 0.51-mm thick and a single detector card employing two ^{6}LiF detectors. The dose equivalent information for x-rays, gamma-rays, and neutrons is determined by making multiple integrations on the glow curves from the detectors [4], or by computer analysis of the glow curves [5-6]. The cadmium shield thickness of 0.51 mm was chosen to optimize the x-ray and gamma-ray response of the badge [7].

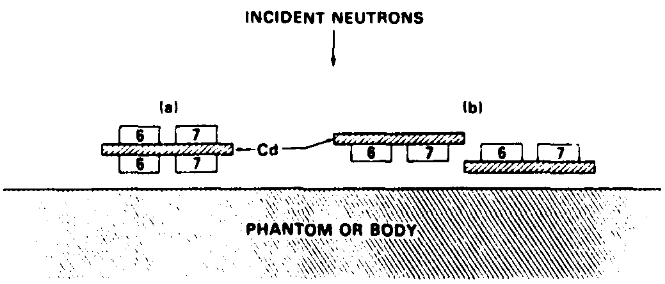

Fig. 1 — Albedo dosimeter configurations: (a) Falk, (b) Navy. The numbers 6 and 7 refer to ^{6}LiF and ^{7}LiF TLD.

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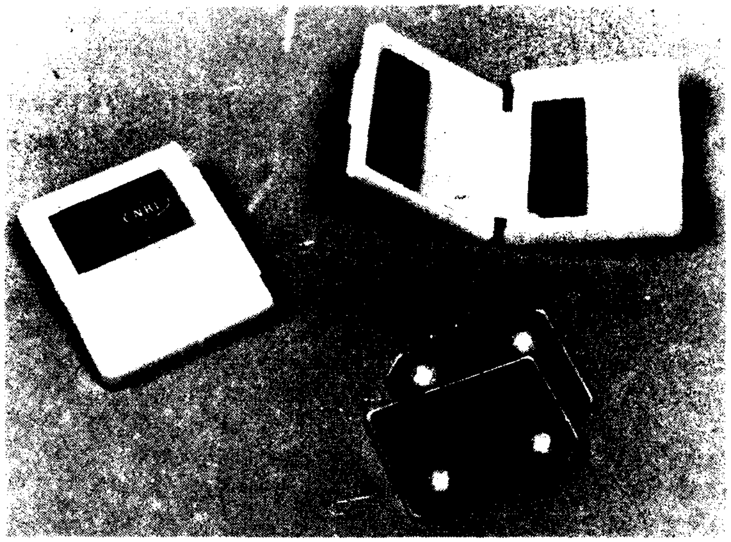

Fig. 2 — The albedo badge used in this study: (left) assembled; open, showing the cadmium filters (right), and the detector cards (center)

THE MODERATED NEUTRON SOURCES

The neutron spectra used in this study were generated by moderating AmBe and ^{252}Cf sources with Lucite, steel, or polyethylene, and with combinations of Lucite and steel. Lucite cylinders having wall thicknesses of 2, 4, 6, 8, and 10 cm were employed as hydrogenous moderators. Each cylinder had a hole at its center with a diameter of 2.54 cm and a height of 5.1 cm to accommodate the sources as shown in Fig. 3(a). To center the ^{252}Cf source, it was held in an aluminum film can. To achieve greater moderation, Lucite slabs 23 cm in diameter and having thicknesses of 5.1 to 25.4 cm were used as illustrated in Fig. 3(b). For these configurations, the sources were located in a 2.54-cm diameter hole in a 5.1-cm thick slab forming a donut. Additional thicknesses of Lucite slabs were interposed between the source and detectors. Polyethylene spheres from a Bonner sphere spectrometer were also used as hydrogenous moderators. Only ^{252}Cf was used with these moderators since the AmBe source was physically too large to fit into the holes in the spheres. The voids in the spheres normally filled by the detector-phototube assembly were filled with Lucite plugs.

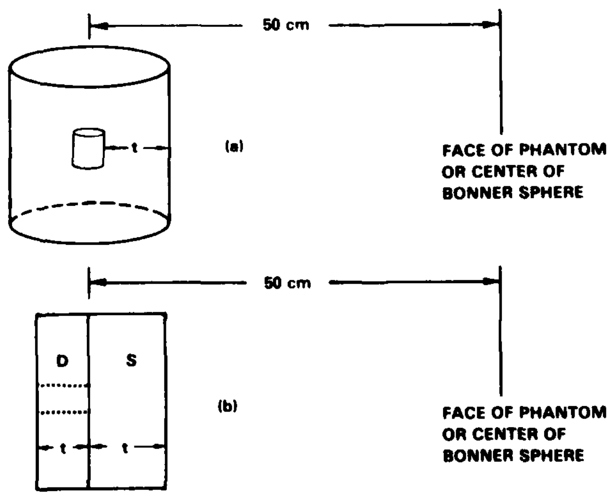

Fig. 3 — Two moderator configurations used to produce the neutron spectra: (a) Lucite cylinders having wall thicknesses *t* of 2, 4, 6, 8, or 10 cm; (b) Lucite or steel donuts *(D)* having a thickness *t* of 5.1 cm plus various thicknesses *t* of Lucite or steel slabs *(S)*

Steel slabs identical to the previously described Lucite slabs were employed as high-Z moderators. In addition, other spectra were generated by adding various thicknesses (5.1 to 20.3 cm) of steel to a 5.1-cm Lucite donut plus a 10.2-cm Lucite slab. Alternatively, steel plus Lucite moderation was obtained by using a 5.1-cm steel donut plus a 10.2-cm steel slab to which various thicknesses of Lucite were interposed between the steel and the detectors. The moderator configurations are described in Tables 1 and 2 by giving, in order, the moderator(s) and thickness(es) from the source toward the detectors.

Table 1 — Summary of the Spectrum Characteristics and Detector Responses for the Moderated ^{252}Cf Spectra

Moderator Configuration[1]	DE[2]	Ave. E[3]	R(3/9)[4]	R(B/9)[5]	TLD(B)[6]	TLD(F)[7]
None	1.00	2.20	0.50	0.05	1.00	0.36
LC(2.0)	0.89	1.49	0.95	0.12	1.67	0.96
LC(4.0)	0.73	1.33	1.35	0.40	2.63	2.44
LC(6.0)	0.57	1.13	1.56	0.86	3.85	4.48
LC(8.0)	0.44	1.20	1.64	1.33	4.54	6.58
LC(10.0)	0.33	1.29	1.69	1.75	5.26	7.85
LD(5.1)	1.26	1.34	0.98	0.25	2.12	1.48
LD(5.1)+LS(5.1)	0.69	1.12	1.54	1.15	4.35	5.37
LD(5.1)+LS(10.2)	0.32	1.28	1.45	1.75	4.55	7.22
LD(5.1)+LS(15.2)	0.15	1.36	1.39	2.04	4.54	7.32
LD(5.1)+LS(20.3)	0.08	1.34	1.56	2.33	4.55	6.89
LD(5.1)+LS(25.4)	0.05	1.13	1.96	2.78	4.35	6.49
SD(5.1)	1.43	1.64	0.56	0.04	1.00	0.38
SD(5.1)+SS(5.1)	1.12	1.28	0.69	0.05	1.25	0.51
SD(5.1)+SS(10.2)	0.73	1.01	0.85	0.08	1.43	0.59
SD(5.1)+SS(15.2)	0.48	0.83	1.00	0.13	1.79	0.80
SD(5.1)+SS(20.3)	0.32	0.71	1.16	0.18	2.22	1.09
LD(5.1)+LS(10.2)+SS(5.1)	0.17	1.14	1.30	0.68	2.94	2.63
LD(5.1)+LS(10.2)+SS(10.2)	0.10	0.91	1.47	0.81	3.03	2.46
LD(5.1)+LS(10.2)+SS(15.2)	0.07	0.70	1.67	1.19	3.57	2.97
LD(5.1)+LS(10.2)+SS(20.3)	0.05	0.59	2.00	1.54	4.17	3.97
SD(5.1)+SS(10.2)+LS(5.1)	0.28	0.74	1.96	1.06	4.17	4.13
SD(5.1)+SS(10.2)+LS(10.2)	0.12	0.71	2.17	2.22	5.26	7.41
SD(5.1)+SS(10.2)+LS(15.2)	0.07	0.63	2.44	2.56	5.26	7.31
SD(5.1)+SS(10.2)+LS(20.3)	0.05	0.55	2.78	2.63	5.00	6.41
PBS(2.54)	0.79	1.72	0.87	0.15	1.66	0.80
PBS(3.8)	0.68	1.47	1.16	0.36	2.44	1.73
PBS(6.4)	0.47	1.30	1.49	1.10	3.85	4.38
PBS(10.2)	0.25	1.42	1.45	2.04	5.00	7.58
PBS(12.7)	0.16	1.47	1.43	2.33	5.00	8.33
PBS(15.2)	0.11	1.65	1.35	2.38	5.26	8.77

(1) Symbol meaning: LC-Lucite cylinder, LD-Lucite donut, LS-Lucite slab, SD-steel donut, SS-steel slab, PBS-polyethylene Bonner sphere. Moderator thickness (cm) is in parentheses.

(2) Dose equivalent determined from the Bonner sphere spectrum, normalized to the unmoderated ^{252}Cf source.

(3) Average neutron energy (MeV) calculated from the unfolded Bonner sphere spectrum (does not include thermal neutrons)

(4) The response of the Eberline 3 in. detector divided by the response of the Eberline 9-in. Remmeter.

(5) The response of the Eberline bare tube detector divided by the response of the Eberline 9-in. Remmeter.

(6) Neutron response of the ^{6}LiF detector behind the cadmium shield, normalized to TLD *(B)* for the unmoderated ^{252}Cf spectrum.

(7) Neutron response of the ^{6}LiF detector in front of the cadmium shield, normalized to TLD *(B)* for the unmoderated ^{252}Cf spectrum.

Table 2 — Summary of the Spectrum Characteristics and Detector Responses for the Moderated AmBe Sources

Moderator Configuration[1]	DE[2]	Ave. E[3]	R(3/9)[4]	R(B/9)[5]	TLD(B)[6]	TLD(F)[7]
None	1.00	4.60	0.34	0.06	0.78	0.26
LC(2.0)	0.92	3.67	0.59	0.10	1.23	0.59
LC(4.0)	0.81	3.34	0.78	0.27	1.75	1.27
LC(6.0)	0.70	2.90	0.88	0.56	2.22	2.22
LC(8.0)	0.60	2.83	0.92	0.81	2.50	3.09
LC (10.0)	0.51	2.87	0.93	1.02	2.77	3.90
LD(5.1)	1.05	2.86	0.75	0.21	1.69	1.17
LD(5.1)+LS(5.1)	0.71	2.81	0.89	0.63	2.50	2.84
LD(5.1)+LS(10.2)	0.44	2.96	0.79	0.80	2.38	2.90
LD(5.1)+LS(15.2)	0.25	3.08	0.84	0.92	2.50	3.29
LD(5.1)+LS(20.3)	0.15	3.22	0.92	0.97	2.44	3.25
LD(5.1)+LS(25.4)	0.09	2.55	1.09	1.21	2.70	3.42
SD(5.1)	1.21	2.81	0.44	0.04	1.11	0.40
SD(5.1)+SS(5.1)	0.86	1.87	0.58	0.06	1.43	0.53
SD(5.1)+SS(10.2)	0.55	1.41	0.75	0.09	1.69	0.68
SD(5.1)+SS(15.2)	0.35	1.08	0.92	0.14	1.92	0.83
SD(5.1)+SS(20.3)	0.23	0.84	1.10	0.20	2.27	1.06
LD(5.1)+LS(10.2)+SS(5.1)	0.23	2.40	0.84	0.36	1.82	1.30
LD(5.1)+LS(10.2)+SS(10.2)	0.13	1.50	1.01	0.48	2.22	1.49
LD(5.1)+LS(10.2)+SS(15.2)	0.09	1.08	1.23	0.69	2.50	1.77
LD(5.1)+LS(10.2.)+SS(20.3)	0.06	0.89	1.45	0.89	2.94	2.30
SD(5.1)+SS(10.2)+LS(5.1)	0.25	0.21	1.43	0.77	3.57	3.43
SD(5.1)+SS(10.2)+LS(10.2)	0.12	1.31	1.52	1.28	3.85	5.13
SD(5.1)+SS(10.2)+LS(15.2)	0.08	1.35	1.69	1.49	3.70	4.81
SD(5.2)+SS(10.2)+LS(20.3)	0.05	1.16	1.92	1.59	3.84	4.74

(1) Symbol meaning: LC-Lucite cylinder, LD-Lucite donut, LS-Lucite slab, SD-steel donut, SS-steel slab. Moderator thickness (cm) is in parentheses.

(2) Dose equivalent determined from the Bonner sphere spectrum, normalized to the unmoderated AmBe spectrum.

(3) Average neutron energy (MeV) calculated from the unfolded Bonner sphere spectrum (does not include thermal neutrons).

(4) The response of the Eberline 3-in. detector divided by the response of the Eberline 9-in. Remmeter.

(5) The response of the Eberline bare tube detector divided by the response of the Eberline 9-in. Remmeter.

(6) Neutron response of the ^{6}LiF detector behind the cadmium shield, normalized to TLD*(B)* for the unmoderated ^{252}Cf spectrum.

(7) Neutron response of the ^{6}LiF detector in front of the cadmium shield, normalized to TLD*(B)* for the unmoderated ^{252}Cf spectrum.

The spectra were determined by using a set of Bonner spheres manufactured by the Ludlum Instrument Co., Sweetwater, Texas. A 4 × 4-mm ^{6}LiI scintillation crystal was used as the thermal neutron detector in the center of polyethylene moderators having diameters of 2, 3, 5, 8, 10, and 12 in. The spectra were also characterized by using a bare BF_3 detector tube, a 9-in. spherical Remmeter, and a cadmium-covered 3-in. polyethylene moderator which used the BF_3 to detect the thermal neutrons at its center. These detectors were manufactured by the Eberline Instrument Co., Santa Fe, New Mexico. An Anderson-Braun-type Remmeter, the Navy AN/PDR-70, was also used to determine the dose equivalent [8].

METHOD FOR CORRECTING DOSIMETER RESPONSE

To correct for the energy dependence of personnel dosimeters, it is convenient to assume that the response of the dosimeter is some linear combination of the detectors used to characterize the neutron spectrum, i.e.,

$$R(D) = k_1 R_1 + k_2 R_2 + \ldots + k_n R_n, \quad (1)$$

where $R(D)$ is the response of the dosimeter, $R_1 \ldots R_n$ are the responses of the detectors, and $k_1 \ldots k_n$ are calibration factors. For example, the response of a completely cadmium-covered albedo neutron dosimeter is often characterized by response of the Eberline 9-in. and 3-in. detectors [2].

$$R(Cd) = k_1 R(9 \text{ in.}) + k_2 R(3 \text{ in.}) \quad (2)$$

where $R(Cd)$ is the response of the albedo dosimeter, $R(9 \text{ in.})$ is the response of the 9-in. detector, and $R(3 \text{ in.})$ is the response of the 3-in. detector. Since the 9-in. detector is a Remmeter, we may divide by its response to get response per Rem,

$$R(Cd)/\text{Rem} = k_1 + k_2 R(3/9), \quad (3)$$

where R(3/9) is equal to R(3 in.) $R(9 \text{ in.})$. The albedo dosimeters used by the Navy are not completely covered with cadmium, hence we anticipated that their response would also be related to the response of a thermal neutron detector, e.g., the Eberline bare BF_3 tube. Adding this detector to describe the Navy albedo badge response, Eq. (3) takes the form

$$R(A)/\text{Rem} = k_1 + k_2 R(3/9) + k_3 R(B/9), \quad (4)$$

where $R(A)$ is the response of the detector behind the cadmium shield in the Navy albedo badge, and $R(B/9)$ is the response of the bare BF_3 detector divided by the response of the 9-in. Remmeter. Note also that the response of the albedo TLD may be related to the response of the instruments through other more complicated functions and equations. As previously stated, one of the purposes of this study was to determine the relationship between the response of the albedo dosimeter and the instruments used to characterize the neutron spectra.

EXPERIMENTAL PROCEDURE

All irradiations were made with the sources at the center of a calibration room having dimensions of 4.7-m wide, 7.1-m long, and 3.5-m high. The walls and floor are of concrete or concrete block, and the ceiling is corrugated steel covered by tar and gravel. Irradiations were made with the sources, and the centers of the detectors or phantom, 1.5 m above the floor. Source to detector or phantom distance was 50 cm in all cases, as illustrated in Fig. 3. The bare sources and the smaller Lucite cylinders (2 to 6-cm wall thickness) and polyethylene balls (2.5, 3.8, and 6.4-cm radius) were supported on foam blocks held in a ring stand, and the heavier moderators were supported on a steel stand. The Bonner sphere detectors were supported on their Ludlum stand for the spectra determinations. The AN/PDR-70 and Eberline 9-in. Remmeters were supported on a 20 × 20 × 0.6-cm steel plate screwed on the top of the Ludlum stand in place of the phototube detector assembly. For the Eberline 3-in. and bare tube measurements, the detectors were held by a clamp fastened to a ring stand to reduce scattered neutrons. Because the calibration room is relatively small, the scattered neutron fluence from the walls is not insignificant even at 50 cm. It is approximately 15% of the direct fluence for the bare ^{252}Cf source. The scattered dose equivalent is considerably less; for the bare ^{252}Cf source, Eisenhauer et al. [9] have determined it to be approximately 5% of the direct dose equivalent. For the spectra characterizations, total counts for each detector were at least 10,000 so that the counting error was less than 1%. The neutron spectra were unfolded from the Bonner sphere data by using the Sanna response matrix [10,11] and the MAXIET algorithm [12,13] in the YOGI unfolding code [14].

The dosimeter badges were exposed on a 60 × 30 × 20-cm thick water-filled Lucite phantom having wall thicknesses of 0.64-cm. Source to surface of phantom distance was 50 cm. The albedo dosimeter badges were positioned so that the detectors were 8 mm from the surface of the phantom. No corrections to the dose equivalent were made from the actual source to detector distance in accordance with the recommendations of Schwartz and Eisenhauer [15]. Groups of four albedo dosimeters were exposed for 16 h to each spectrum. This gave total ^{6}LiF readings equivalent to 300 to 3000 mR of ^{60}Co gamma radiation. After readout, the cards were given a ^{60}Co calibration exposure of 300 mR and read again. The corrected ^{7}LiF readings were subtracted from the ^{6}LiF readings to give the neutron

response per Rem for each spectrum. Since all exposures were of the same duration, and readout and calibration schedules were identical for all spectra, no corrections for loss or gain of detector sensitivity before exposure, or loss or gain of stored thermoluminescence signal after exposure, were necessary.

RESULTS AND DISCUSSION

The results of the experiments to determine spectral characteristics, survey instrument response, and dosimeter response are summarized in Table 1 for the ^{252}Cf spectra and in Table 2 for the AmBe spectra. The response of the TLDs per Rem was determined by using the AN/PDR-70 Remmeter to determine the dose equivalent. We have chosen to use the Remmeter data, rather than the data derived from the spectra, because the Remmeter is the standard method of dose equivalent determination used in the Navy. The Remmeter data generally agreed with the dose equivalent determined from the spectrum within ±3%, and in no case exceeded ±10%. It is interesting to note the increase in dose equivalent for the Lucite and steel donuts. This is caused by extra neutrons being scattered toward the detectors by the donuts. For both sources, note that the two thickest moderators reduce the dose equivalent by about a factor of 20, and the average energy by about a factor of 5. From these tables we see that the response of the TLDs per Rem, the average neutron energy, and the detector ratios are almost constant for hydrogenous moderator thicknesses exceeding approximately 10 cm, while the responses for the steel moderators are still changing with increased moderator thickness. This indicates that there is little spectral change for hydrogenous moderators exceeding 10-cm thickness, but that this is not the case for the steel moderators. This conclusion is supported by the Bonner sphere spectra and is in agreement with calculations [16].

To better understand the response of the albedo badge as a function of spectral characteristics, and to determine the best method of correcting for its energy dependence, we plotted on linear and log scales the response of the detector behind the cadmium shield, TLD*(B)*, vs various detector ratios or spectral characteristics. The best fit to the data was then made by minimizing the sum of the squares of the deviations of the TLD response from the line [17].

The response of the albedo detector vs the Eberline 3-in. to 9-in. detector ratio is shown in Fig. 4. We see that the response per Rem of the TLD varies by a factor of seven for these spectra, and that the predicted variation will exceed a factor of 15 for 3-in. to 9-in. ratios between 0.2 and 3.0. As previously discussed, we see the clustering of the hydrogenous moderator data for the thicker moderators. Note the general increased response per Rem for the hydrogenous moderators. We attribute this to the thermal neutron response of this type of albedo dosimeter. These neutrons are not detected by the cadmium covered 3-in. detector, resulting in 3-in. to 9-in. ratios that are too small for these spectra. Removing all or part of the cadmium should increase this ratio and give a better fit to the data. The equation of the line shown in Fig. 4, the best least squares fit to the data, is

$$\ln [\mathrm{TLD}(B)/\mathrm{Rem}] = 1.06 \ln R(3/9) + 0.852. \tag{5}$$

The root-mean-square (rms) deviation of the detector response from the line is ±22.1%. The slope of the line, 1.06, is in good agreement with the value, 1.13, derived from the data in Ref. 1 for a completely cadmium-covered albedo dosimeter, supporting the conclusion that all albedo dosimeters have essentially the same energy dependence [18,19]. The linear equation best fitting the same data is

$$\mathrm{TLD}(B)/\mathrm{Rem} = 2.30\, R(3/9) + 0.156, \tag{6}$$

which gives an rms error of ±22.2%. Note that we do not give the errors, derived directly from the data analysis, on the coefficients describing the lines since most of the deviation from the line is caused by spectral differences rather than experimental errors in the data. We estimate that the errors in the TLD data are less than ±5%, hence, the errors on the coefficients of the lines are less than ±1% due to experimental errors. However, these coefficients might be significantly different for a different set of spectra. The total rms error includes the error due to spectral differences and experimental error.

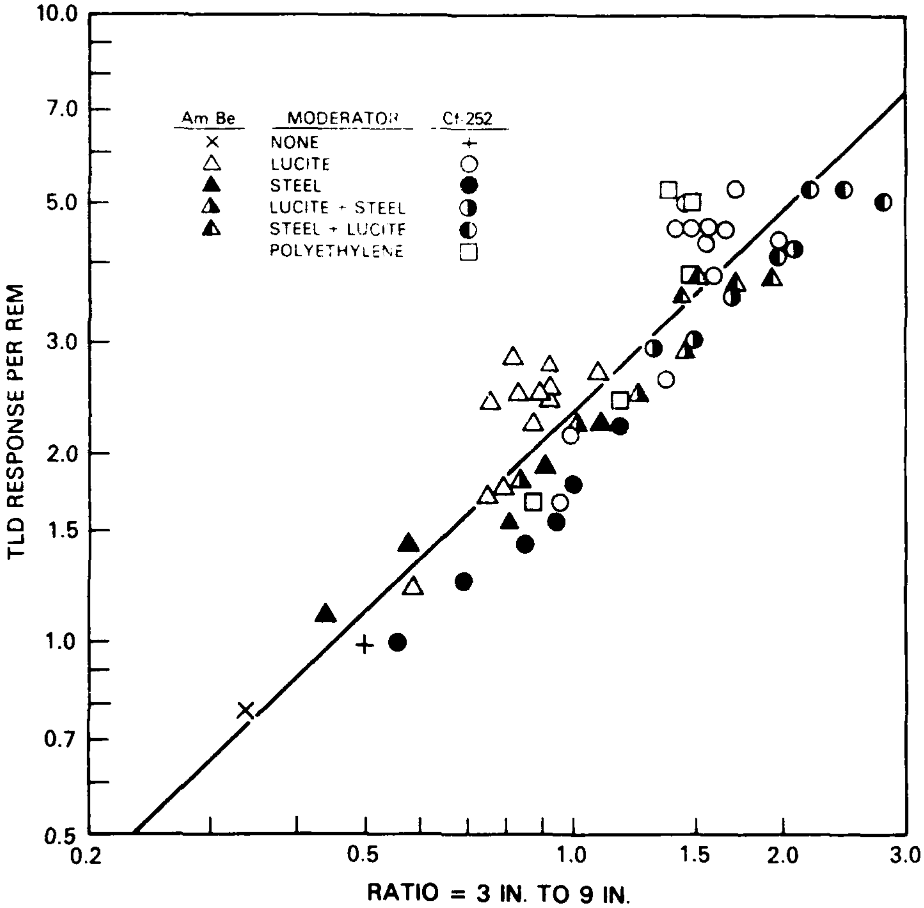

Fig. 4 — The neutron response per Rem of the ^{6}LiF detector behind the cadmium shield vs the 3-in. to 9-in. detector ratio

Since the experimental error is relatively small, the error due to spectral differences is essentially the same as the total error. The rms error due only to spectral differences for Eq. (5) is ±21.5%; for Eq. (6) it is ±21.6. Henceforth, only the rms error due to spectral differences will be given since this is the parameter of primary interest.

The response of the albedo detector, TLD*(B)*, vs the Eberline bare to 9-in. detector ratio is shown in Fig. 5. The equation best fitting the data is

$$\ln [\mathrm{TLD}(B)/\mathrm{Rem}] = 0.376 \ln R(B/9) + 1.22, \tag{7}$$

which gives an rms error of ±14.7%. The linear equation fitting the same data is

$$\mathrm{TLD}(B)/\mathrm{Rem} = 1.56\, R(B/9) + 1.53, \tag{8}$$

which gives an rms error of ±17.6%. Thus, for these particular spectra, the bare to 9-in. ratio gives a better indication of albedo response than the 3-in. to 9-in. ratio. We caution that this equation may not be directly applicable to other spectra. Hankins has shown that the thermal neutron fluence varies widely for different radiation environments and that the response of a completely cadmium-covered dosimeter cannot be predicted by the thermal fluence [20]. This is not surprising considering that the Hankins-type albedo dosimeter has negligible thermal neutron response; this is not the case for the

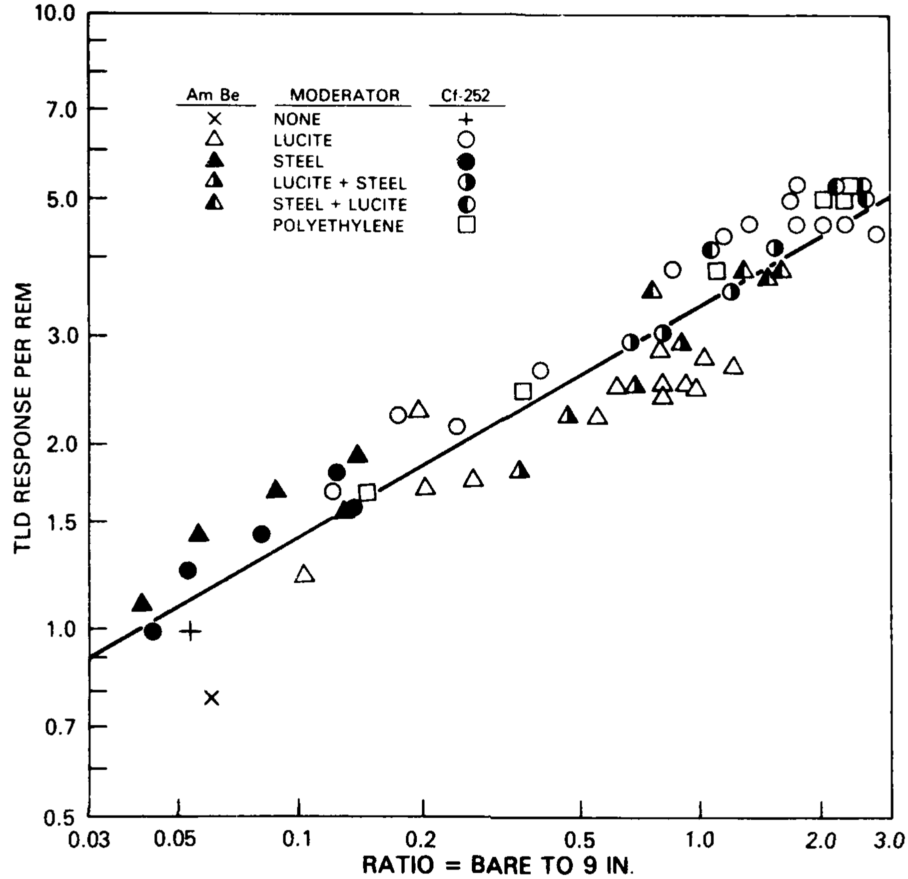

Fig. 5 — The neutron response per Rem of the ^{6}LiF detector behind the cadmium shield vs the bare to 9-in. detector ratio

dosimeter used in this study. However, since the thermal component is highly dependent on the composition of the moderating and absorbing materials in the environment, we do not recommend using this equation in other environments without first determining its applicability.

As we have previously pointed out, the use of both ratios should give the best results, and this is the case. The albedo response using both ratios is predicted by the linear equation

$$\mathrm{TLD}(B)/\mathrm{Rem} = 0.861\ R(3/9) + 1.12\ R(B/9) + 0.879, \qquad (9)$$

which gives an rms error of ±12.5%. In addition to these spectra, we have found that this equation also gives a good indication of dosimeter response for other spectra generated in steel and cadmium environments that produce, for the same 3-in. to 9-in. ratios, bare to 9-in. ratios considerably greater than those shown in Tables 1 and 2. Equation (9) again suggests that it should be possible to design a single field detector to adequately predict the response of the dosimeter. Optimizing the size of the moderator, removing all or part of the cadmium cover, or drilling a series of holes into the cadmium and the polyethylene should result in a single detector giving a response suitable for reducing the energy dependence of this type of albedo dosimeter.

The response per Rem is predicted even better by the empirical equation

$$\mathrm{TLD}(B)/\mathrm{Rem} = 1.21\ [R(3/9)]^{0.6} + 1.92\ [R(B/9)]^{0.6}, \qquad (10)$$

which gives an rms error of ±10.4%. The TLD(B) response per Rem obtained by using this equation vs the 3-in. to 9-in. ratio is plotted in Fig. 6.

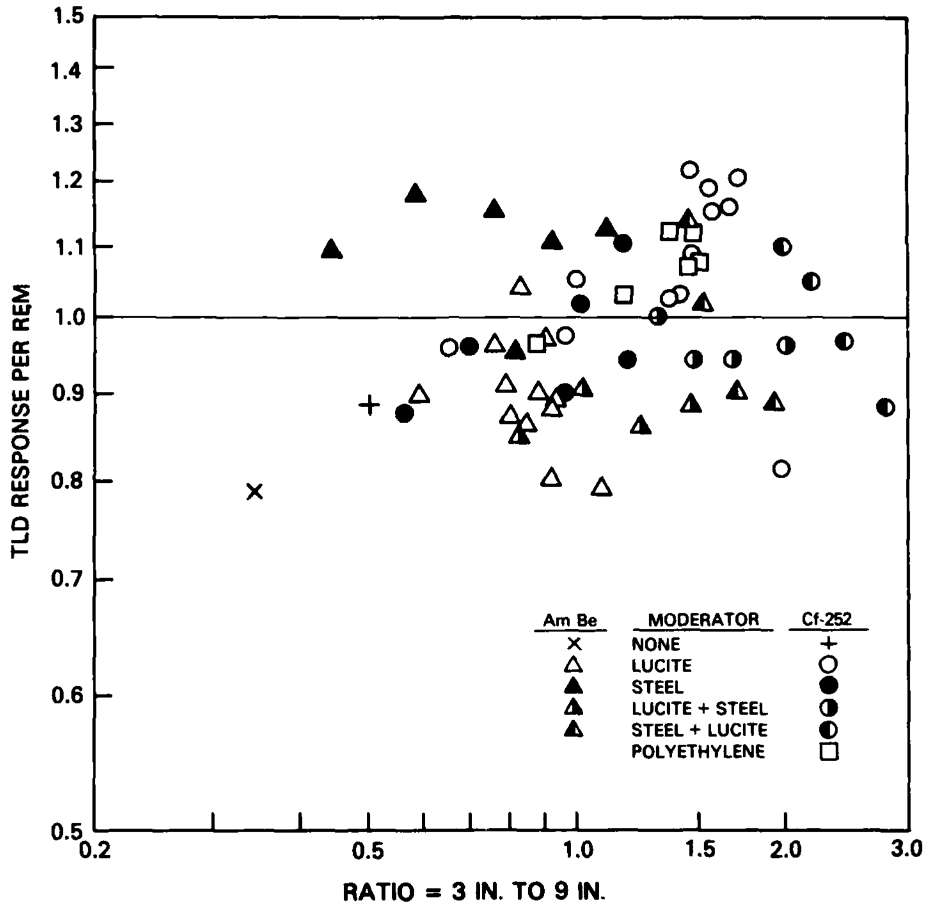

Fig. 6 — The neutron response per Rem of the ^{6}LiF detector behind the cadium shield, corrected by using Eq. (10), vs the 3-in. to 9-in. detector ratio

For cases where survey instrument data are not available to make a correction to the response of the TLD behind the cadmium filter of the albedo badge, it is possible to determine a correction factor based on the ratio of a TLD in front of the cadmium filter to the one behind the filter. The response per Rem of the TLD behind the filter vs the ratio TLD(F) to TLD(B) is plotted in Fig. 7. The equation of the line is

$$\ln\,[\mathrm{TLD}(B)/\mathrm{Rem}] = 0.865\,\ln\,[\mathrm{TLD}(F)/\mathrm{TLD}(B)] + 1.11, \tag{11}$$

which gives an rms error of ±21.2%. The linear equation fitting the same data is

$$\mathrm{TLD}(B)/\mathrm{Rem} = 2.70\,[\mathrm{TLD}(F)/\mathrm{TLD}(B)] + 0.357, \tag{12}$$

which gives an rms error of ±21.4%. Thus we see that for these spectra the detector ratio in the albedo badge can be used to determine a correction factor for the TLD behind the cadmium shield. Since the TLD in front of the cadmium responds mostly to incident thermal neutrons, the cautions expressed regarding the use of the bare to 9-in. detector ratio are applicable. The steel moderator data in this figure suggest that using this ratio for spectra produced with thicker steel moderators might result in considerable overestimation of the dose equivalent. Since steel moderators and rooms are not uncommon in Navy environments, this limits the usefulness of this method for many of our applications. The method is routinely used at NRL, however.

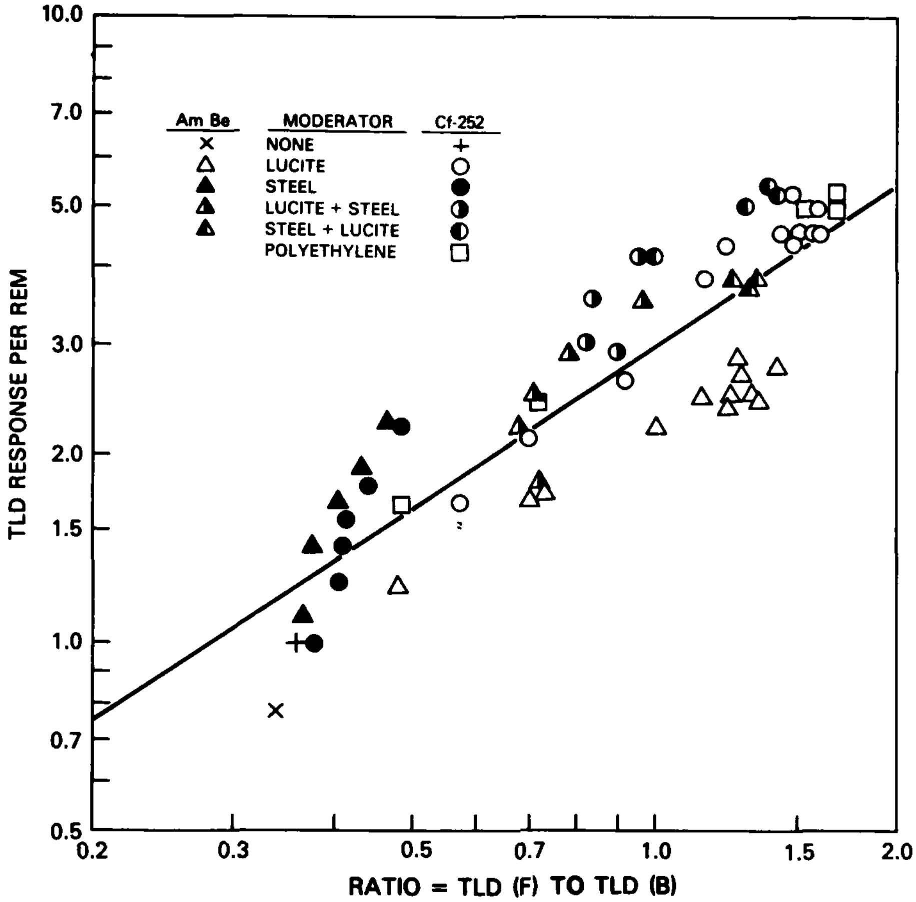

Fig. 7 — The neutron response per Rem of the ^{6}LiF detector behind the cadmium shield vs the TLD *(F)* to TLD *(B)* detector ratio

The average energy of a neutron spectrum can also be derived by using survey instruments that determine energy fluence and particle fluence. Therefore we attempted to use the average energy of the spectrum to predict albedo badge response, but this did not work as well as the other methods. We also attempted to use the various detector ratios to determine a correction factor for the average reading of the two detectors, sometimes used as a measure of dose equivalent [21], but this did not give results as good as using only the detector behind the cadmium filter as the albedo dosimeter.

CONCLUSIONS

We have determined the response of an albedo neutron dosimeter badge to 56 moderated neutron spectra. The response of the albedo TLD per Rem varied by a factor of seven for the range of spectra studied. Our experiments have shown that it is possible to significantly reduce this energy dependence by using measurements made with neutron survey instruments. We have shown that a thermal neutron detector and a Remmeter are superior to a 3-in. detector and Remmeter for this particular type of albedo dosimeter. As expected, the use of all three detectors gave the best results. Our results suggest that a single detector can be designed to replace the bare and 3-in. detectors. This conclusion is supported by some of our recent experiments which have shown that the inner portion of the AN/PDR-70 Remmeter and the complete AN/PDR-70 give results as good as those obtained by using the bare, 3-in., and 9-in. detectors. For the spectra used in this study, a second detector in the badge can provide a

correction factor to give results equal in accuracy to those obtained by using the 3-in. to 9-in. ratio, but not the bare to 9-in. ratio.

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